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INVESTIGATION OF BLUNT FIN-INDUCED FLOW SEPARATION REGION ON A FLAT PLATE AT MACH NUMBERS 2.5 TO 4.0

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

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FOREWORD

The work reported herein was done for and at the request of Aerospace Research Laboratories (ARL), Hypersonic Research Laboratory (ARR) Dayton, Ohio, under Program Element 61102F, Project 7064.

The results presented herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-71-C-0002. The tests were conducted from July 14 to 22, 1970, under ARO Project No. VD0082, and the manuscript was submitted for publication on September 25, 1970.

This technical report has been reviewed and is approved.

Emmett A. Niblack, Jr. Lt Colonel, USAF AF Representative, VKF Directorate of Test	Joseph R. Henry Colonel, USAF Director of Test

ABSTRACT

Tests were conducted at Mach numbers 2.5 to 4.0 to investigate the effects of cylindrically blunted fins on the flow over a flat plate at zero angle of attack. The free-stream Reynolds number, based on the distance from the blunt fin to the flat plate leading edge, ranged from 2.8×10^6 to 4.7×10^6. Pitot pressure profiles were obtained in the fin-induced flow separation region. Increasing the thickness of the fin was found to increase the size of the three-dimensional separation area. Pressure distributions as well as examples of the oil flow and schlieren photographic coverage are presented.

CONTENTS

APPENDIXES

NOMENCLATURE

M_∞	Free-stream Mach number
p	Measured pressure, psia
p_o	Tunnel stilling chamber pressure, psia
p'_o	Normal shock pressure recovery, psia
p_∞	Free-stream static pressure, psia
Re_{x_F}	Free-stream Reynolds number based on fin location (x_F)
T_o	Tunnel stilling chamber temperature, °R
x, y, z	Coordinate for model surface pressure locations (see Fig. 1b), in.
x_F	Distance from the fin to the leading edge of flat plate, in.
x_p	Axial distance from fin leading edge to pitot probe (positive upstream), in.
z_p	Vertical distance from flat plate surface to probe, in.
Δz	Spacer block thickness (used with fin 1.000 only), in.

Note: Configuration nomenclature is given in Fig. 1.

SECTION I
INTRODUCTION

A test program to investigate the turbulent boundary layer separation induced by various size blunt fins mounted on a flat plate was conducted in the 12-in. Supersonic Wind Tunnel (D) of the von Kármán Gas Dynamics Facility (VKF). These tests were a continuation and extension of previous work (Ref. 1) which used a 9-in.-wide flat plate. The present test used a flat plate that spanned the tunnel (12-in. wide) and also a larger fin (1.000-in. diameter) with remotely driven pitot probes to survey the fin-induced flow separation region.

Static pressure and pitot pressure survey data as well as oil flow and schlieren photographs were obtained at free-stream Mach numbers 2.5, 3, and 4 over a range of free-stream Reynolds numbers, based on fin location (x_F), from 2.8 x 10^6 to 4.7 x 10^6. The tests were conducted with the flat plate at zero angle of attack.

SECTION II
APPARATUS

2.1 MODEL

The model (see Fig. 1, Appendix I) consisted of a flat plate with a sharp leading edge and three interchangeable cylindrically blunted fins of different thickness that could be mounted on the flat plate centerline. The flat plate, which spanned the wind tunnel, had 28 static pressure orifices on the surface and the two wider fins had 8 and 11 pressure orifices, respectively, on the cylindrical leading edge.

The widest fin (1.000 in.) also had two remotely driven pitot probes (see Fig. 1) which were used to obtain axial surveys in the flow separation region. The upper probe had an axial travel of approximately 0.6 in., while the lower probe, which was larger in diameter, could traverse 2.0 in. Spacer blocks were utilized with the 1.000-in. fin to obtain surveys at various vertical stations.

2.2 INSTRUMENTATION

Model surface pressures and fin leading edge and probe pressures were measured with 15- and 60-psid transducers, respectively, which were referenced to a near vacuum. The transducers were calibrated for ranges of 6.7-, 33-, and 100-percent of full scale, and the range was automatically selected to give the best measurement precision. Model flow field schlieren and oil flow photographs were obtained during the test.

2.3 WIND TUNNEL

Tunnel D is an intermittent, variable density wind tunnel with a manually adjusted, flexible plate-type nozzle and a 12- by 12-in. test section. The tunnel operates at Mach numbers from 1.5 to 5 at stagnation pressures from about 5 to 60 psia and at stagnation temperatures up to about 80°F. A description of the tunnel and airflow calibration information may be found in Ref. 2.

SECTION III
TECHNIQUES AND PRECISION

3.1 DATA ACQUISITION

Axial and lateral flat plate surface pressure distributions were obtained for all three fins, and fin leading edge pressures were obtained on the two larger fins. Maximum Reynolds numbers were run at each test condition to obtain a turbulent boundary layer upstream of the flow separation. A boundary layer trip was used to ensure turbulent flow at Mach number 4.0. A probing system was used with the largest fin (1.000 in.) to obtain pitot pressure profiles in the flow separation region. Only one probe was traversed at a time to minimize disturbances. The lower probe was extended axially until it was observed to intersect the separation shock or alter the separation flow field. Spacers (Δz) were used to raise the 1.000-in. fin in 1/32-in. increments so that pitot surveys could be obtained at various vertical locations. The blunt fin leading edge pressures as well as flat plate pressures were also recorded with the 1.000-in. fin at several vertical positions.

The schlieren system was used to monitor the pitot probe traverse and observe the variations in the separation region. Schlieren photos were recorded at all test conditions at which the blunt fin - flat plate combination were run to assist in the definition of the flow separation region. Oil flow photographs were also obtained of all configurations tested, at one or more test conditions. A complete test summary is presented in Table I (Appendix II). The tunnel conditions at which the tests were conducted are given below:

M_∞	p_o, psia	p_o', psia	p_∞, psia	T_o, °R	$Re_{x_F} \times 10^{-6}$
2.50	46	23.0	2.6	530	4.64
2.99	60	19.9	1.7	530	4.71
4.00	60	8.3	0.4	530	2.78

3.2 DATA PRECISION

The uncertainties for the tunnel conditions p_o, T_o, and M_∞ were estimated from calibration of the p_o and T_o instruments and examination of tunnel flow uniformity and repeatability. From repeat calibrations, the estimated model surface and pitot pressure measurement precision was ±0.003 psia or ±0.2 percent whichever was greater. The uncertainties were combined assuming random combination to compute the uncertainties in the parameters listed below.

	Uncertainty in Percent						
M_∞	M_∞	p_o	T_o	p_∞	Re_{x_F}	p/p_∞	p/p_o'
2.5	±0.4	±0.2	±1.0	±1.6	±1.6	±1.6	±0.8
3.0	0.2	0.2	1.0	0.9	1.5	1.0	0.6
4.0	0.2	0.2	1.0	0.8	1.5	0.9	0.6

SECTION IV
RESULTS AND DISCUSSION

Graphic representation of the flow processes being investigated is presented in the oil flow and schlieren photographs in Fig. 2. The flow separation region on the flat plate, which was produced by the blunt fin, is clearly indicated by the oil flow photographs (Fig. 2a). The schlieren photographs (Fig. 2b) indicate the vertical and axial region of separation at various Mach numbers. It should be noted that the top two schlieren photographs were obtained with an exposure of one microsecond and the bottom two photographs with an exposure of one millisecond. An indication of unsteady flow in the separation region is evidenced by the lack of crispness of the one millisecond exposure photographs.

The effects of fin thickness on the axial, lateral, and vertical fin leading edge surface pressures at Mach number 3.0 are presented in Fig. 3. As expected, increasing the fin width produced a larger three dimensional separation region. This is also consistent with the trends established in Ref. 1. The distribution shown for Configuration 0.750 is a combination of data obtained for blunt fin locations (x_F) of 5.85 and 5.73 in. The separation location as determined from the oil flow photographs in Fig. 2a and the separation shock origin determined from schlieren photographs in Fig. 2b for Configuration 1.000 are also shown on the axial distribution.

The effect of Mach number on the model flow field is shown in Fig. 4. The Mach number 4.0 data without boundary-layer trips were of a different nature than the lower Mach number data as shown in the axial pressure distribution and the oil flow photographs (Fig. 2a). This is probably indicative of transitional boundary-layer separation since the expected length of laminar and transitional flow was approximately 4.7 in. (Ref. 3), which would locate transition to fully turbulent flow downstream of the beginning of the interaction region (~3.6 in. from the flat plate leading edge, from oil flow photographs in Fig. 2a). The addition of a boundary-layer trip (0.007-in.-thick serrated fiber glass tape located at 0.8 in. downstream of the flat plate leading edge) confirmed this conclusion since the Mach number 4.0 data trends with a trip agree with those obtained at Mach number 3.0 where naturally turbulent flow was expected. The separation locations scaled from the oil flow photographs (Fig. 2a) and separation shock origins (Fig. 2b) are also shown on the axial distribution and generally coincide with the start of the pressure rise. The fin leading edge pressure distribution at Mach number 2.5 shows that the separation region moved further up the fin leading edge than at Mach numbers 3.0 or 4.0. Surface pressures in a three-dimensional separation region are expected to be lower than those computed, assuming a two-dimensional wedge with equivalent shock wave angle (determined from schlieren photographs); however, the axial distribution at Mach number 2.5 indicates pressures in the separation region which are approximately twice the two-dimensional level. Examination of the pressure data and schlieren photographs does not indicate unusual changes in the flow field, and no explanation for this apparent discrepancy can be given.

The flat plate axial and 1.000-in.-diam fin leading edge surface pressure distributions for Mach number 3.0 are shown in Fig. 5 for various fin heights (Δz variations). The

fin surface pressure plot indicates that the separation region extended to about z = 1.0 in. (see also Fig. 2b). The axial pressure distributions indicate a dependency on the fin height Δz in the separation region which was not expected. The fin pressure distributions show no apparent effect of fin height indicating that the vertical extent of the separation region did not change. The fin bow shock shape may have been altered slightly by the fin height which could have affected the interaction of the fin shock with the separation shock; however, no measurable difference in the shock shape could be detected by examination of the schlieren photographs. The flow separation and separation shock origin locations from Fig. 2 are also indicated.

The results of the pitot probe surveys are presented in Fig. 6. The traverses at the lower values of z_p ($z_p \leq 12/32$ in.) show pressures that were lower than the normal shock recovery pressure, and had trends which differed from the upper traverses. Difficulty with the lower probe altering the flow field separation shock location is indicated in the lower traverses (z_p = 8/32, 10/32, and 12/32 in.) by the approach of the pressure ratio to the free-stream asymptote of unity for lower values of x_p than expected. That is, the asymptote should not be reached until the probe extended through the separation shock, which is indicated by the dashed line in Fig. 6. All traverses with the large probe were continued until the probe attained a free-stream pitot reading (i.e., the probe was upstream of the separation shock). The one overlap traverse with the two pitot probes (z_p = 24/32 in.) shows good agreement until the region of the separation shock was approached.

The probe interference problem is shown graphically by a series of schlieren photographs in Fig. 7. These pictures correspond to the z_p = 8/32-in. probe traverse shown in Fig. 6. The separation region appears unaltered as the probe is extended to 0.58 in.; however, extending the probe to x_p = 0.79 in. caused a complete collapse of the separation region. This problem apparently occurred on all probe runs as the separation shock was approached; however, the severity of the problem decreased as z_p increased.

SECTION V
CONCLUDING REMARKS

Three cylindrically blunted fins were tested on a flat plate to investigate three-dimensional fin induced boundary layer separation. Tests were conducted at Mach numbers 2.5, 3.0, and 4.0 at free-stream length Reynolds numbers of 2.8 x 10^6 to 4.7 x 10^6. A summary of the results from these tests is presented below:

1. Increasing the thickness of the cylindrically blunted fin increased the separation region at Mach number 3.0.

2. Pitot pressure profiles were obtained with two probes traversing in the fin-induced separation region and show good agreement at the one overlap point (z_p = 24/32 in.). The probe, however, produced a disturbance when it approached the separation shock; the effect of which decreased with increasing z_p.

REFERENCES

1. Young, F. L., Kaufman, L. G., and Korkegi, R. H. "Experimental Investigation of Interactions between Blunt-Fin Shock-Wave and Adjacent Boundary Layers at Mach Numbers 3 and 5." ARL 68-0214, December 1968.

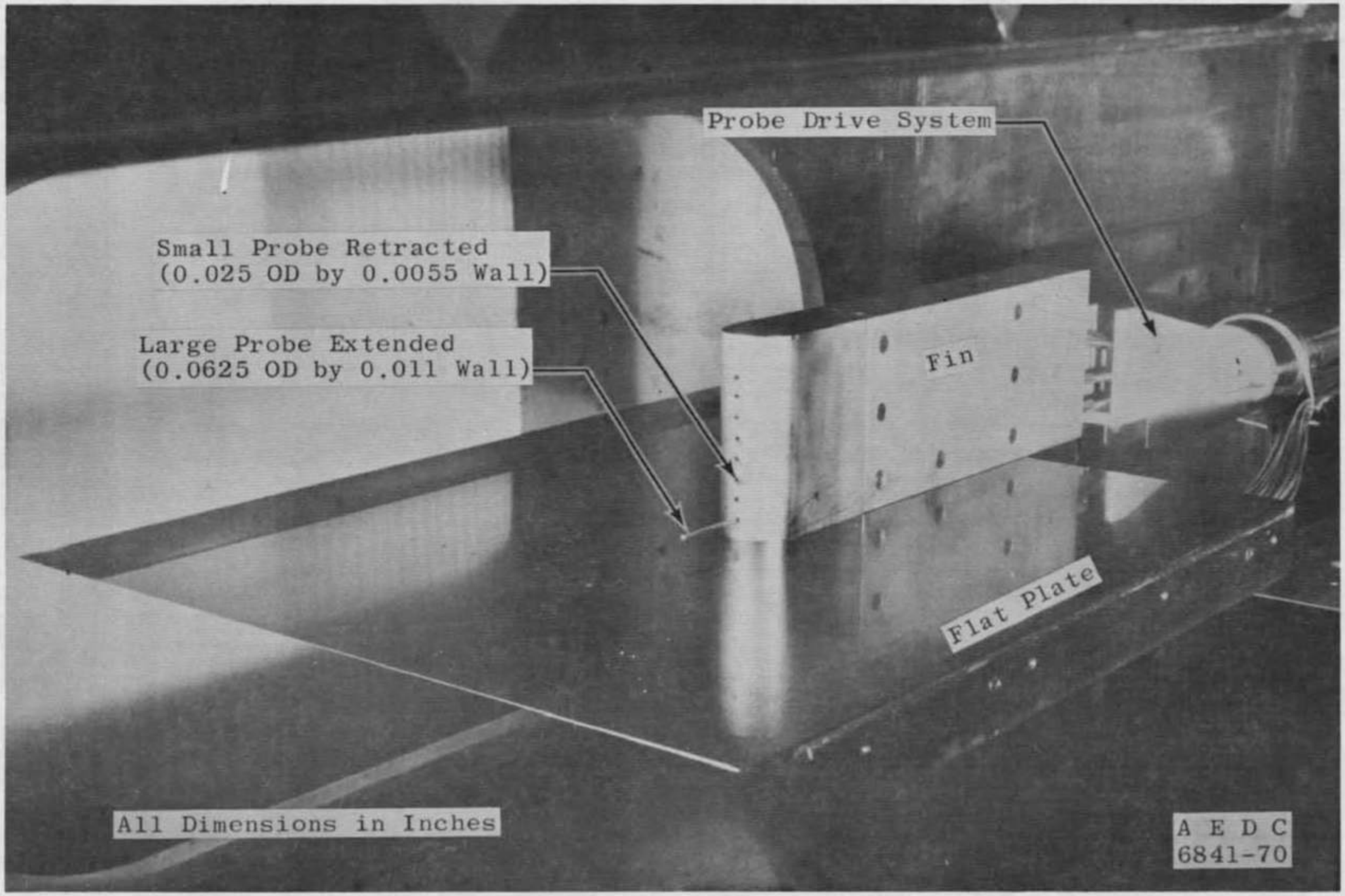
2. Anderson, A. "Flow Characteristics of a 12-in. Intermittent Supersonic Tunnel." AEDC-TDR-63-203 (AD418578), September 1963.

3. Schueler, C. J. "A Comparison of Transition Reynolds Numbers from 12-in. and 40-in. Supersonic Tunnels." AEDC-TDR-63-57 (AD299290), March 1963.

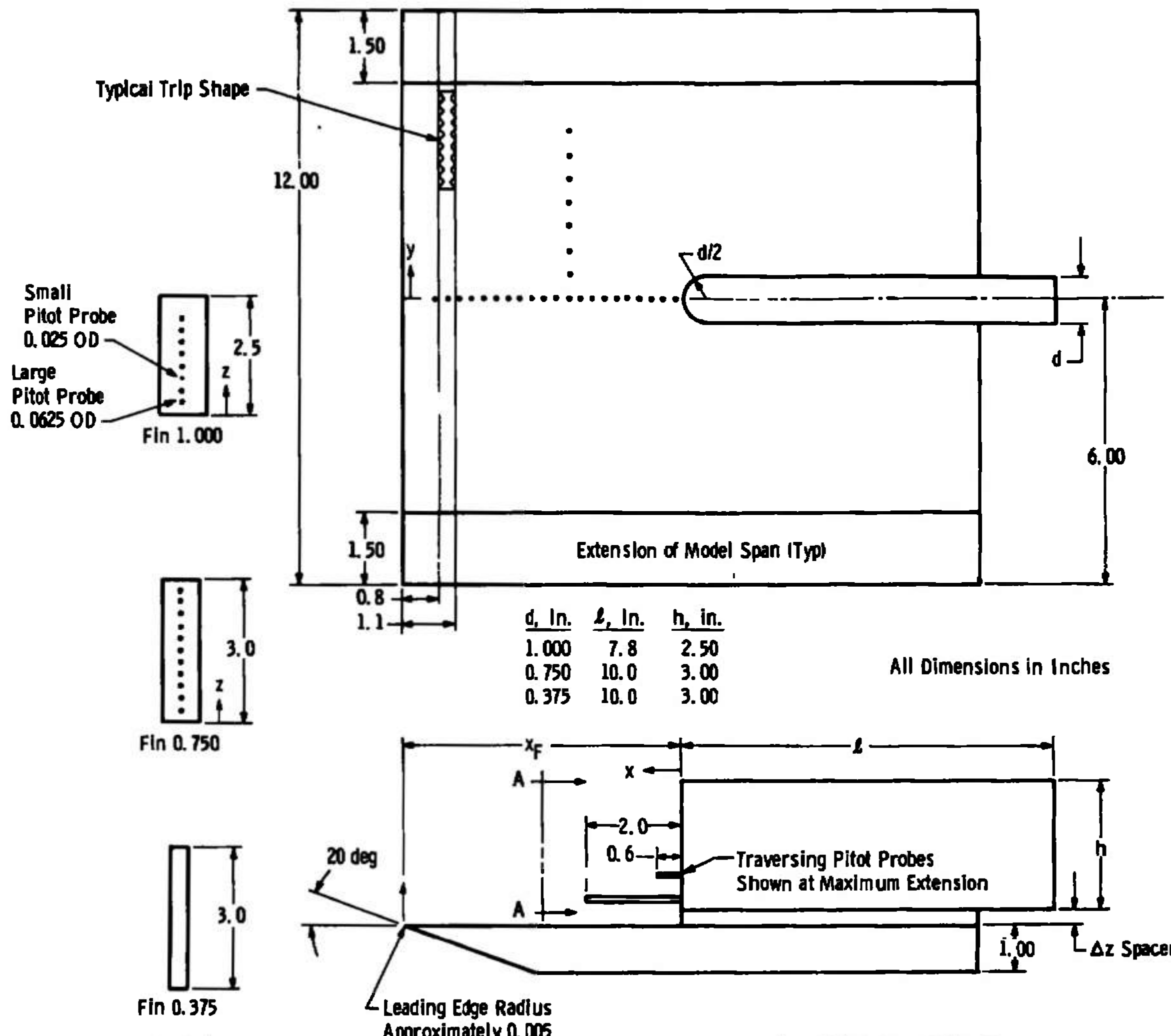
APPENDIXES

I. ILLUSTRATIONS

II. TABLE



a. Configuration 1.000 Installed in the Wind Tunnel
Fig. 1 Model Details



d, in.	ℓ, in.	h, in.
1.000	7.8	2.50
0.750	10.0	3.00
0.375	10.0	3.00

Plate Pressure Orifice Locations
$x_F = 5.85$ ① $(z = 0)$

x, in.	y, in.	x, in.	y, in.
5.169	0	1.670	0
4.915		1.415	
4.667		1.167	
4.415		0.919	
4.167		0.670	
3.917		0.417	
3.665		0.169	
3.417		2.415	0.495
3.165			0.988
2.917			1.484
2.665			1.990
2.415			2.484
2.164			2.989
1.918			3.488

①To obtain the x locations for $x_F = 5.73$ subtract 0.125 in. from each x coordinate.

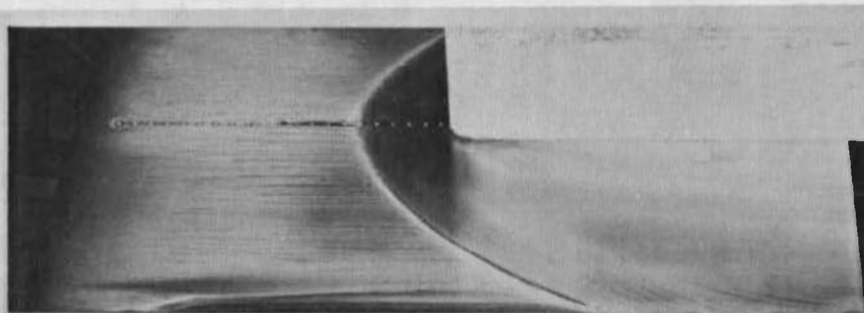
Fin Leading-Edge Pressure Orifice Locations $(x = 0)$

Fin 1.000 z, in.	Fin 0.750 z, in.
0.250*	0.250
0.507	0.499
0.750*	0.747
1.005	0.996
1.259	1.246
1.509	1.496
1.758	1.721
2.007	1.996
	2.247
*Probes	2.497
	2.745

No Pressure Orifices on Fin 0.375

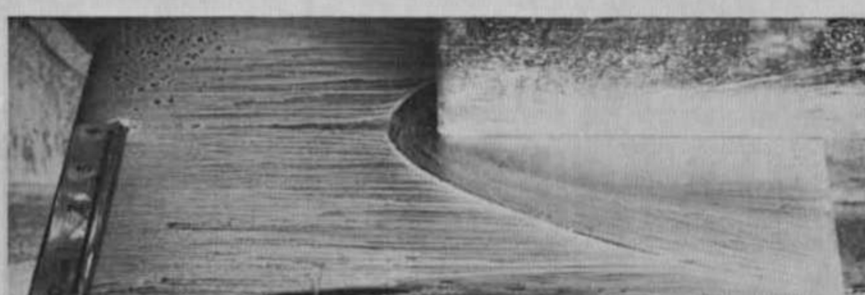
Δz Heights x 32, in.
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16

b. Model Sketch
Fig. 1 Concluded

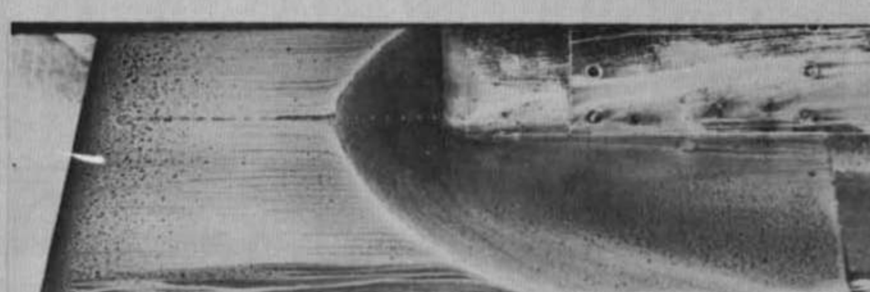


Configuration 0.750, M_∞ = 2.50, Re_{x_F} = 4.6 x 10^6

Configuration 0.750, M_∞ = 4.00, Re_{x_F} = 2.8 x 10^6,
Without Boundary Layer Trips

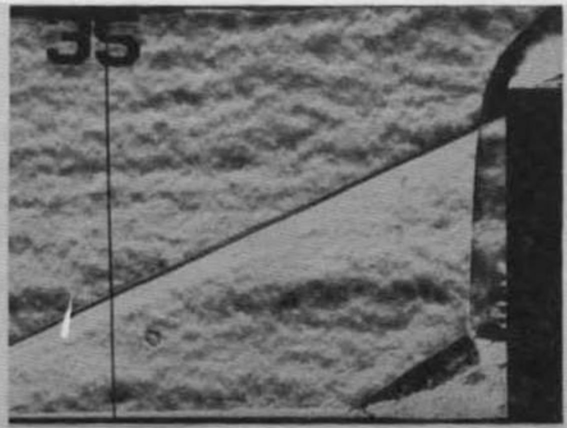


Configuration 0.375, M_∞ = 4.00, Re_{x_F} = 2.8 x 10^6

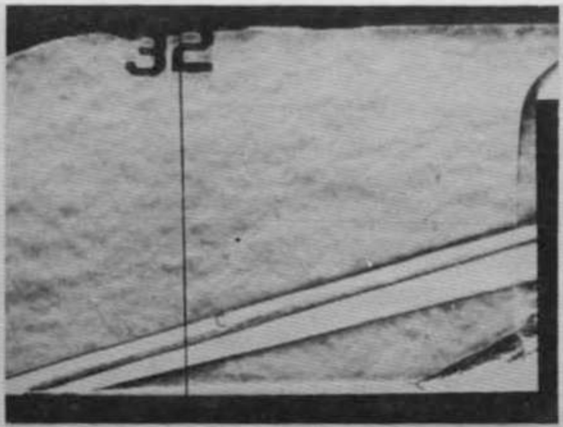


Configuration 1.000, M_∞ = 2.99, Re_{x_F} = 4.7 x 10^6

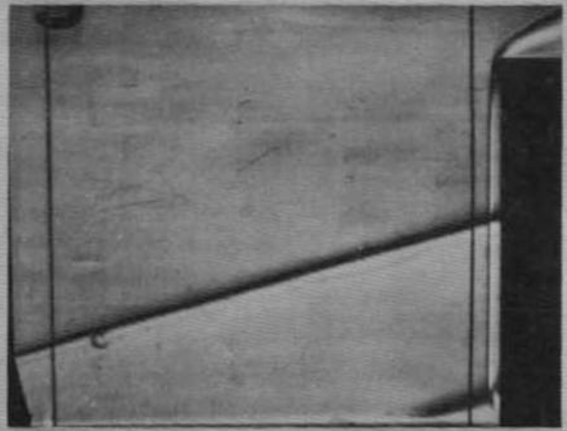
a. Typical Oil Flow Photographs
Fig. 2 Model Flow Field Visualization, x_F = 5.85 in.



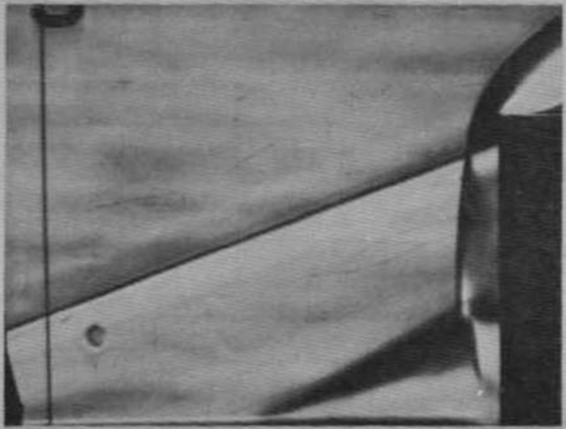
Configuration 0.750, M_∞ = 2.50, Re_{x_F} = 4.6 x 10^6
(Exposure One Microsecond)



Configuration 0.750, M_∞ = 4.00, Re_{x_F} = 2.8 x 10^6
With Boundary Layer Trip
(Exposure One Microsecond)



Configuration 0.375, M_∞ = 4.00, Re_{x_F} = 2.8 x 10^6
(Exposure One Millisecond)



Configuration 1.000, M_∞ = 2.99, Re_{x_F} = 4.7 x 10^6
(Exposure One Millisecond)

b. Typical Schlieren Photographs
Fig. 2 Concluded

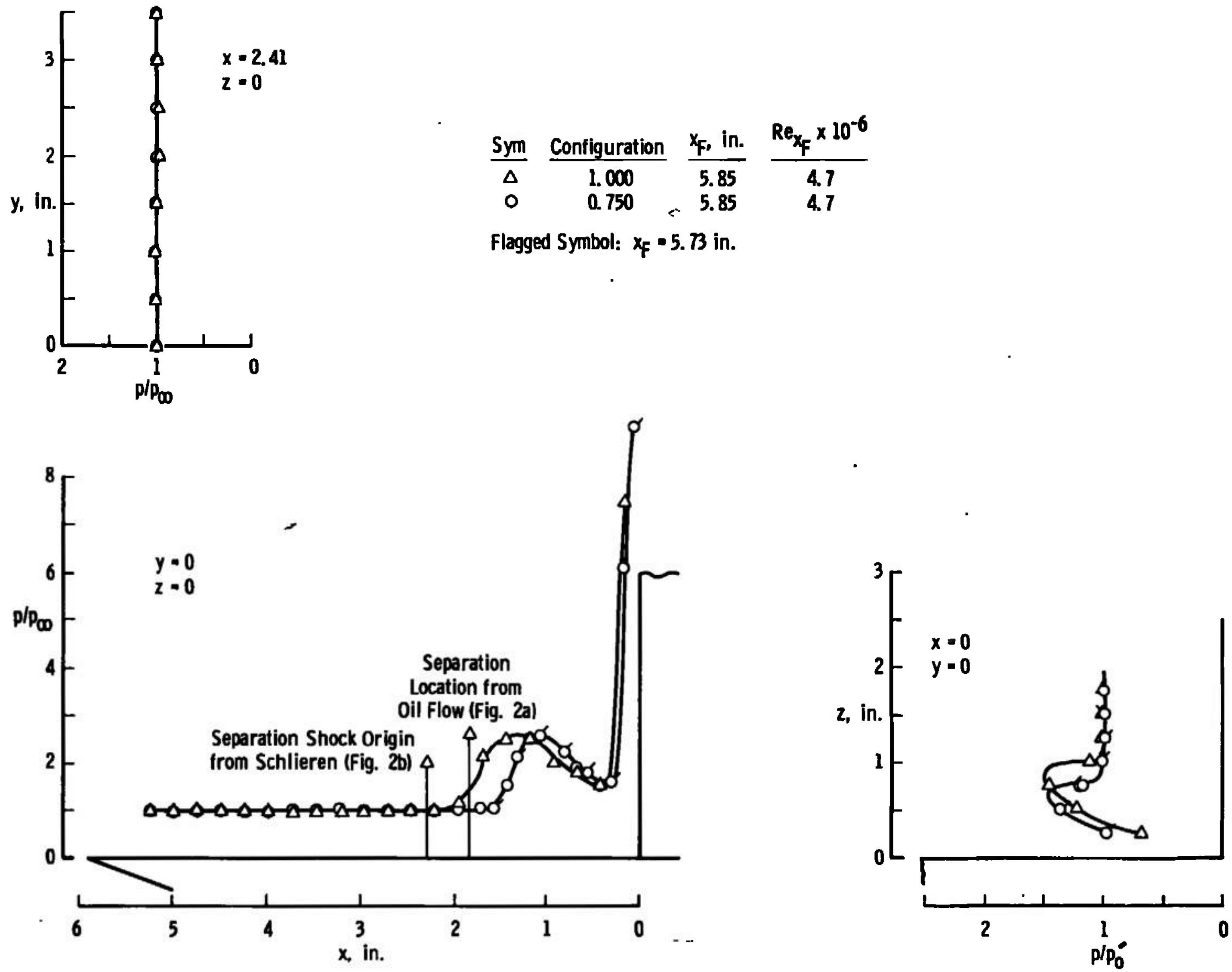


Fig. 3 Fin Thickness Effects on the Model Pressure Distribution at Mach Number 2.99

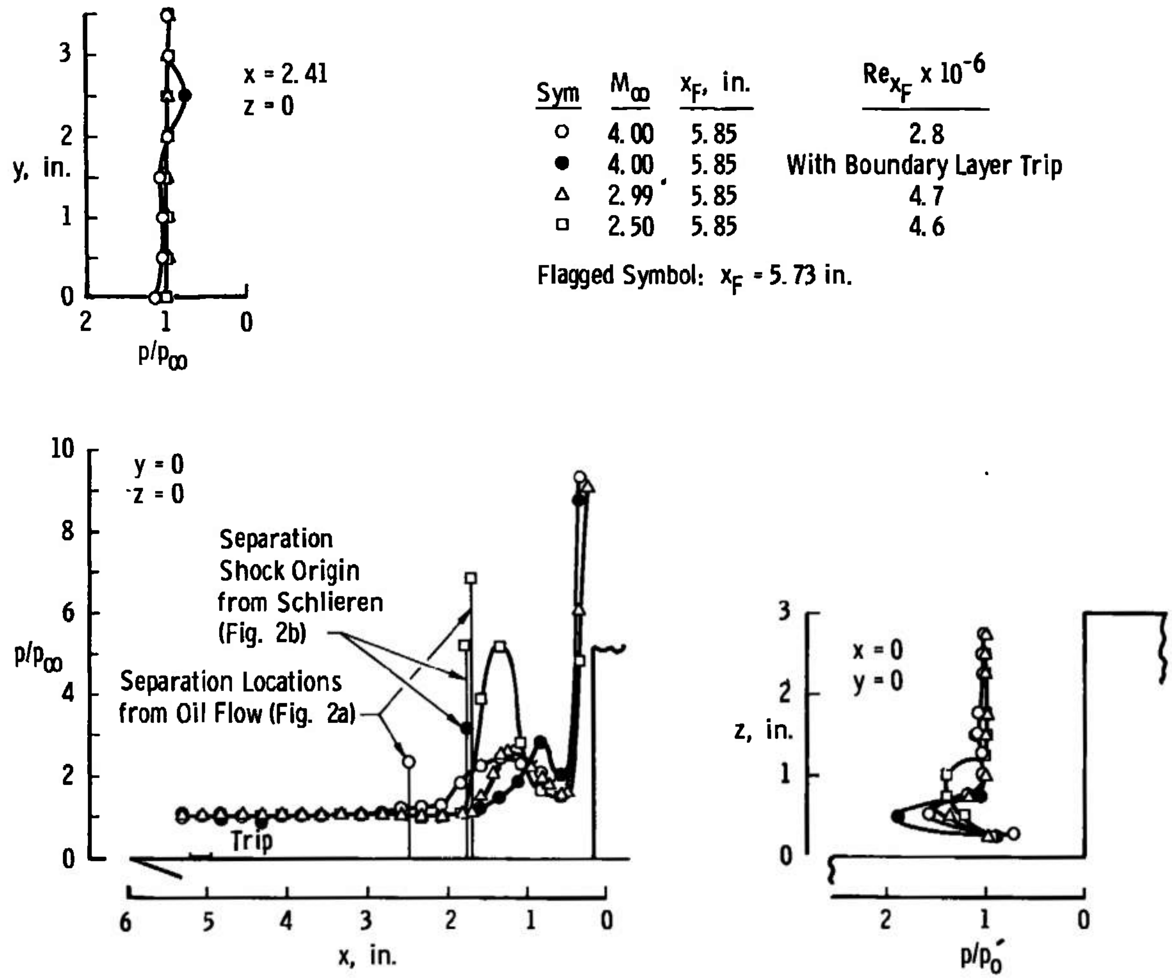


Fig. 4 The Effect of Mach Number on the Pressure Distribution of Configuration 0.750

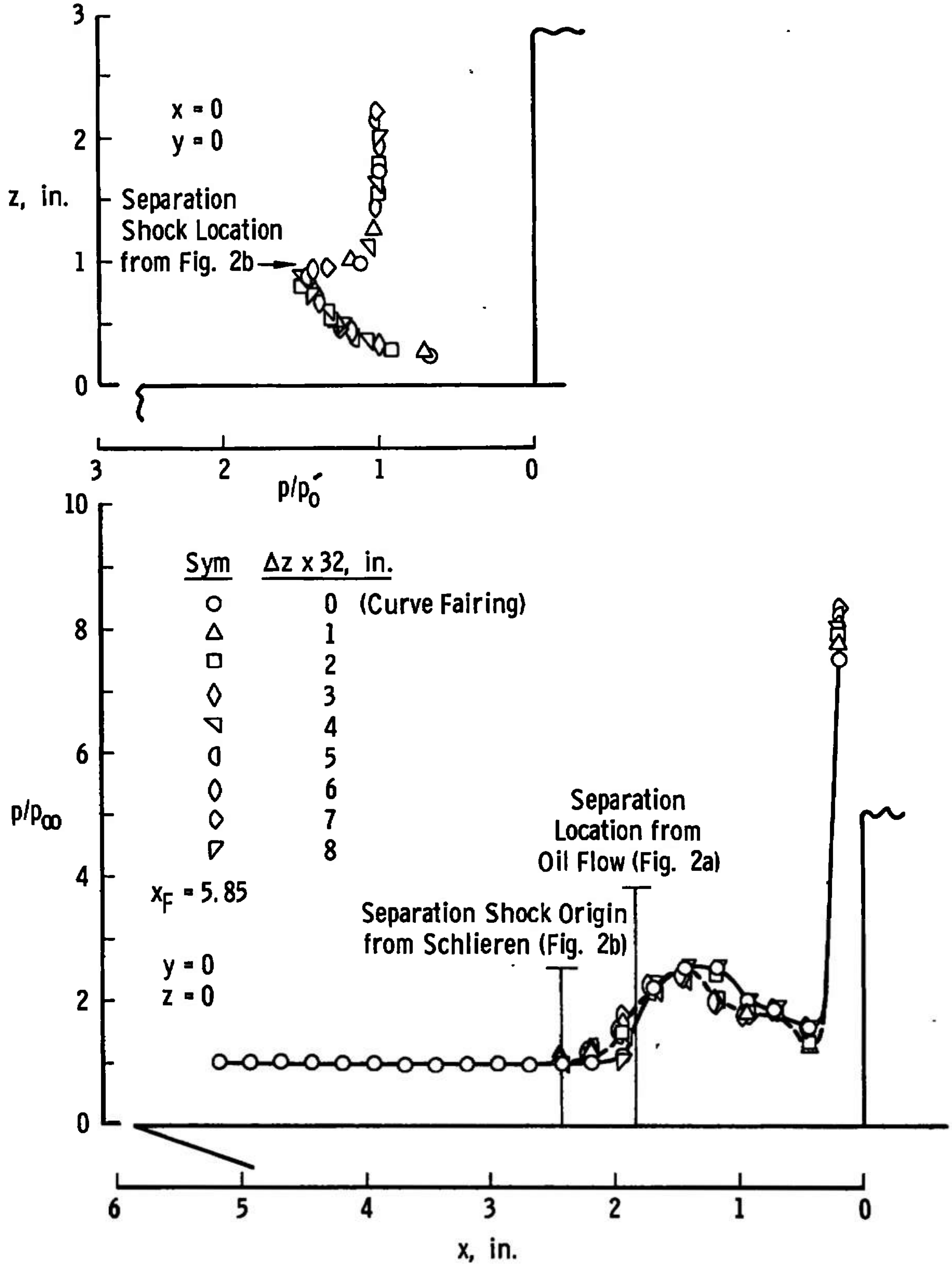


Fig. 5 Pressure Distribution on Configuration 1.000 at M_∞ = 2.99

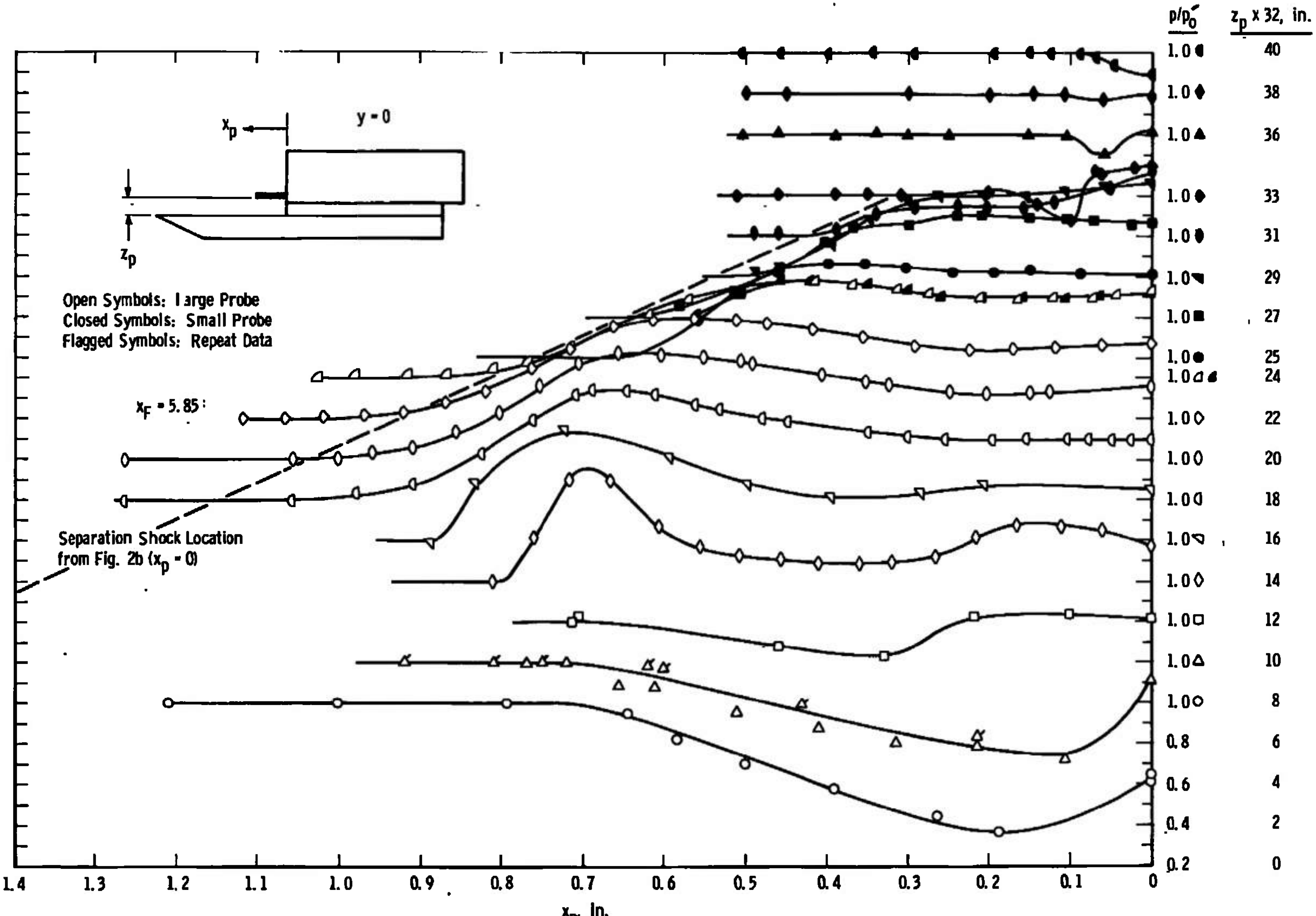


Fig. 6 Pitot Pressure Profiles in the Blunt Fin-Induced Flow Separation Region at $M_\infty = 2.99$, Configuration 1.000, $Re_{x_F} = 4.7 \times 10^6$

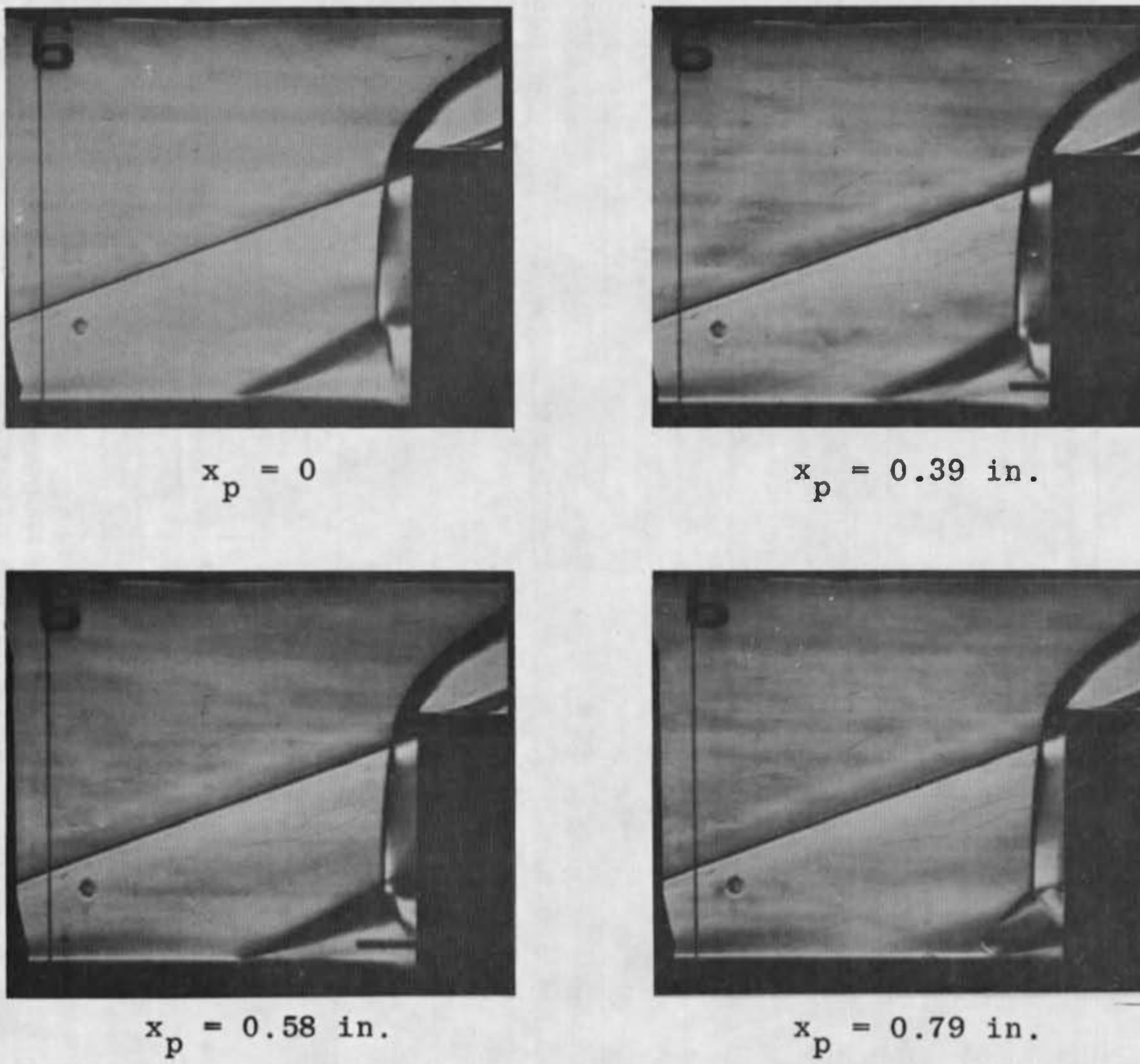


Fig. 7 Schlieren Photographs Showing Probe Interferences at Mach Number 2.99, $Re_{x_F} = 4.7 \times 10^6$, $z_p = 8/32$ in.

TABLE I
TEST SUMMARY
x_F = 5.85 in.

CONFIGURATION	MACH NUMBER 2.5	2.99	4.00	z_p x 32, in.
0.375	S		S	---
0.750	S	S*	S**	---
1.000		S, P		8
		S, P		10
		S, P		12
		S, P		14
		S, P		16
		P		18
		P		20
		P		22
		P		24 Large Probe
		P		24 Small Probe
		S, P		25
		P†		26
		S, P		27
		P†		28
		S, P		29
		P†		30
		S, P		31
		P†		32
		P		33
		P		34
		P		36
		P		38
		P		40

S Model Pressure Data

P Pitot Probe Data

* x_F = 5.85 and 5.725

** With and without boundary layer trip

† Data not presented

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13. ABSTRACT

Tests were conducted at Mach numbers 2.5 to 4.0 to investigate the effects of cylindrically blunted fins on the flow over a flat plate at zero angle of attack. The free-stream Reynolds number, based on the distance from the blunt fin to the flat plate leading edge, ranged from 2.8 x 10^6 to 4.7 x 10^6. Pitot pressure profiles were obtained in the fin-induced flow separation region. Increasing the thickness of the fin was found to increase the size of the three dimensional separation area. Pressure distributions as well as examples of the oil flow and schlieren photographic coverage are presented.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
fins						
flat plate models						
supersonic flow						
Reynolds number						
flow control						
pressure distribution						
pressure profiles						

AFSC
Arnold AFS Tenn